Estimation of Parameters of Network Filter for AC Pulse Regulator

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Abstract. **Estimation of the parameters of filter for AC pulse equipment – regulators, converters is considered in this paper. The way to calculate parameters for the filters on the base of load inductance and switch duty ratio of AC/AC choppers introduced in circuit of reactive load – coil is shown. For damping of current oscillations in a grid circuit LC filter is introduced with the evaluated and presented operation regimes and calculation expressions. Computer modeling is made and the results of mathematical research and computer modeling are shown.**

Keywords: **AC regulator, network, filter, reactive power, capacitor, coil, inductance, switch, duty.**

I. INTRODUCTION

In the last time more often the AC/AC pulse regulators for AC loads are applied operating in buck as well as in boost regimes [1,2,3]. One of the main problems is the coordination of the converters operation with industrial AC network with the aim to reduce current distortions.

The use of AC-switch with commutating reactive loads for energy conversion or for the power factor correction purpose will inevitably cause distortion of the current shape, consumed from the network [1,3]. To improve the shape of the input current close to a sine-form, series or parallel filters are used. Some methods are presented for evaluation of AC/AC chopper operation impact on grid but mostly based on difficult mathematical connections [1,2]. Calculations of filter elements of a filter connected in series with the load using simplified approach and checking correctness of calculations on a computer model are the subject of this work.

II. OVERVIEW OF EQUIPMENT

Circuit of the filter with the switches in the load links is shown in Fig. 1, it consists of a filter choke Lf, in series with the bidirectional switch S1 and capacitor Cf, by-pass switch and the active-inductive load – coil with inductance Lw-, forming a chain like the second order filter. Resistance of the load coil is negligible but all circuit of the coil is by-passed with switch S2 operating in counter-phase with S1.

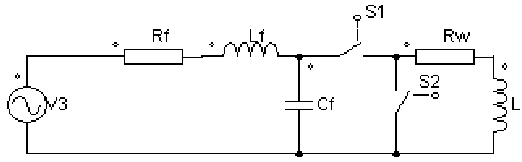

Fig. 1.Scheme of the system with LC filter, connected in series with switched load.

Filter is usually tuned to the frequency $f_f \leq 0.2 \cdot f_m$, where the f_m - switching frequency. However, except for the basic functions - filtering the load current, depending on the chosen parameters, filter elements can consume (for $X_L >> X_C$) or produce (for $X_L << X_C$) the reactive power at the mains frequency. In order to minimize the negative effects the calculation of the parameters depending on the load character is required.

III. ESTIMATION OF PARAMETERS OF NETWORK FILTER

Let us assume that the base switching frequency f_m and the duty ratio γ of the switches in the scheme are constant. In this case, the current of the inductor L_w with negligibly low reactance can be described as:

$$i_{Lw} = \frac{\gamma \cdot U_{cfm} \cdot \sin(\omega t - 0.5\pi)}{\omega L_w}, \qquad (1)$$

where U_{cfm} - the magnitude value of the voltage across the filter capacitor, L_w – inductance of the load inductor. The current supplied from the filter capacitor to the load is with fundamental harmonic $i_1 = \gamma \cdot i_{Lw}$. On the vector diagram of a single-phase circuit the filter inductor current is $\vec{\mathbf{I}}_{\mathbf{Lfm}} = \vec{\mathbf{I}}_{\mathbf{Cfm}} + \vec{\mathbf{I}}_{\mathbf{1m}}$, and the vectors of currents $\vec{\mathbf{I}}_{\mathbf{cfm}}$ and $\vec{\mathbf{I}}_{\mathbf{1m}}$ are both in opposite directions. This means that to get the inductive character of all the system the following relation has to be provided

$$\frac{\gamma^2 U_{cfm}}{\omega L_w} > U_{cfm} \omega C_f \qquad (2)$$

but for capacitive character – the relation has to be opposite.

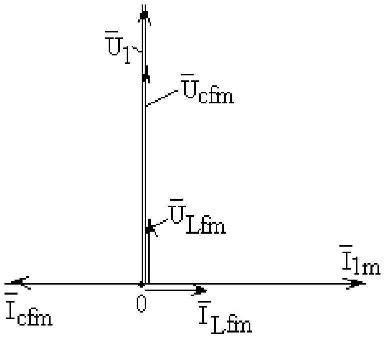

Fig.2. Vector diagram for examined circuit for inductive operation character.

In general case from the vector diagram (Fig.2):

$$U_{cfm}\left(1+\frac{\gamma^2\cdot L_f}{L_w}-\omega^2 L_f C_f\right)=U_{1m} \quad , \qquad (3)$$

where L_f - inductance of filter coil. As at inductive character of the system capacitor's voltage $U_{cfm}<U_{1m}$, it can be stated as:

$$\left(\frac{\gamma^2 L_f}{L_w}-\omega^2 L_f C_f\right)\geq 0 \; . \qquad (4)$$

At the maximum consumption of inductive reactive power duty ratio $\gamma=1$ and

$$Q_{\max}=\frac{U_{Cfm}^2}{2\omega L_w}-U_{Cfm}\omega C_f \; . \qquad (5)$$

Let's assume that relation of voltages $\frac{U_{cfm}}{U_{1m}}=0.9$ in the case of maximum inductive power consumed from the network. In this way the maximum available value of filter inductance L_f can be obtained, and after that it is possible to calculate capacitance C_f. If reactive power of all the system is equal to zero, the following equation is true: $\gamma_{\min}^2=\omega^2 L_w C_f$. Assuming $\gamma_{\min}$, the value of capacitance C_f can be calculated, and after that – the value of inductance L_f.

IV. ESTIMATION OF PARAMETERS OF A FILTER FOR REACTIVE POWER COMPENSATION SYSTEM

In the case if the pulse regulated system operates as a full range reactive power compensation system, the following behavior is necessary. When for switch S1 commutation duty ratio $\gamma=0$ system's behavior is full capacitive; and at switch duty $\gamma=1$ system acts as an inductance. Filter capacitor can be used for production of reactive power, when duty is low – because filter capacitor impedance is greatly higher then filter inductance's impedance at the grid frequency: $X_C \gg X_{Lf}$. For single-phase appliance filter is expected to produce as much reactive power, as it can sink: $Q_{Cf}=Q_S$. As reactive power is equal to $Q=\frac{U^2}{X}$, and capacitor impedance at network frequency is $X_C=\frac{1}{\omega C}$ filter capacitor capacitance can be found in this way:

$$C_f=\frac{Q_S}{U^2\cdot\omega} \; . \qquad (6)$$

Filter inductance can be found from Thompson's equation; admitting filter cut-off frequency is equal to $\omega_C=0.2\cdot\omega_m$, so, filter inductance is equal to

$$L_f=\frac{25}{C_f\cdot\omega_m^2} \; . \qquad (7)$$

Work coil inductance L_w can be found from the reactive power, that system must sink; but the work coil must absorb also all the reactive power, produced by filter capacitor. It means, that work coil consumed reactive power must be double than the system overall compensated reactive power, and on this basis work coil inductance can be found as follows:

$$L_w=\frac{U^2}{2\cdot Q_S\cdot\omega} \; . \qquad (8)$$

For example, if single phase reactive power compensation system of 10kvar at U=230VAC 50Hz grid with switch modulation frequency 5kHz is needed, so on the basis of equations the following system parameters are calculated:

Filter capacitor: $C_f=601.72\mu F$;

Filter inductor: $L_f=42.09\mu H$;

Work coil: $L_w=8.42mH$.

The system with the mentioned parameters has been modeled using PSIM 9.0.

V. NETWORK CURRENT SHAPE DISTORTION ANALYSIS

As it has been stated above the current consumed from filter will be equal to zero, when switch S1 is open, and to following equation, when switch is closed:

$$i_1=\frac{\gamma U_{fm}\sin(\omega t-0.5\pi)}{\sqrt{(\omega L_w)^2+R_w^2}} \quad ,$$

where resistance of the work coil can be accepted as $R_w=0$.

Taking into account the expressions obtained above a reactive power of the whole system relatively to grid is:

$$Q_S=Q_{Lw}-Q_{Cf}=\frac{U_{Cfm}^2}{2}\left(\frac{\gamma}{\omega L_w}-\omega C_f\right) . \qquad (9)$$

Filter coil current is equal to:

$$I_{Lf}=\frac{Q_S}{U_g}=\frac{U_{Cfm}^2}{2U_g}\left(\frac{\gamma}{\omega L_w}-\omega C_f\right) \; . \qquad (10)$$

Let's assume that the capacitor current is relatively low; and being aware that grid's current value is zero at grid voltage u_g maximum, mains voltage can be accepted as:

$$U_{Cfm}=\sqrt{2}U_g \; .$$

In this case, instantaneous grid current will be equal to:

$$i_g=i_{Lf}=\sqrt{2}U_g\left(\frac{\gamma^2}{\omega L_w}-\omega C_f\right)\sin(\omega t-0.5\pi) \; . \qquad (11)$$

As a result in on-duty cycle interval defined by $\frac{\gamma}{f_m}$, where f_m – switch manipulation frequency, capacitor voltage varies on a value of:

$$\Delta U_{Cfon}=\frac{\sqrt{2}U_g\gamma}{f_m C_f}\left(\frac{\gamma(\gamma-1)-\omega^2 C_f L_w}{\omega L_w}\right)\sin(\omega t-0.5\pi) \; . \qquad (12)$$

Maximum voltage deviations will be at the moments when $\omega t = \pi, 2\pi, 3\pi...$, this means that the maximum deviation of the voltage across the filter capacitor will be at the moment, when the basic voltage crosses zero. These deviations distort grid's current.

Calculated by (12) maximum value of capacitors voltage deviations at γ=0.5 and accepted above values of parameters show the value of -14.73 V for $\omega t = \pi$. Simulation of the processes gives full range deviation 15 V, i.e. very close to the calculated value (Fig.3).

In off-duty interval the current of capacitor is equal to i_g value and capacitor voltage

$$\Delta U_{Cfoff} = \frac{\gamma\sqrt{2}U_g}{f_m C_f}\left[\frac{\gamma^2}{\omega L_w} - \omega C_f\right]\sin(\omega t - 0.5\pi) \cdot \qquad (13)$$

Calculated for previous conditions value is -4.93V.

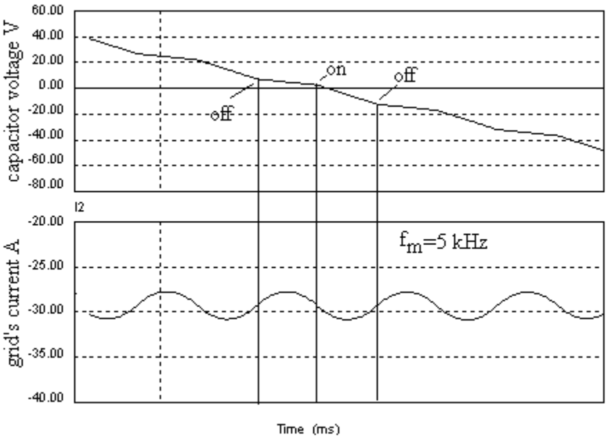

Fig.3. Simulated diagrams of capacitor voltage and grid current at ωt=π .

This deviation of capacitor voltage creates instantaneous voltage difference across the filter inductance, i.e., instantaneous difference between capacitor and grid voltage values. Approximately the magnitude of the difference curve at ωt=π can be calculated as a half of difference between on-duty time decrease of capacitor voltage and voltage change of the fundamental curve in duration of γ / f_m:

$$\Delta U_{Lm} = 0.5(\Delta U_{Cfon} - \omega U_g \sqrt{2}\gamma / f_m) \quad \cdot \qquad (14)$$

For the calculation example the magnitude is 2.45V but full range ripple of current i_g

$$\Delta I_{gm} = 2.\Delta U_{Lm} / (2\pi . f_m . L_f) \cdot \qquad (15)$$

In the case calculated value of current ripple at ωt=π is 3.71 A and this value well coincides with the experimental obtained in computer model of the system.

Maximum values of current i_g ripples take place at $\omega t = \pi, 2\pi, 3\pi...$ and it means that the total ripple "pipe" can be described as

$$\Delta I_g = \Delta I_{gm} \sin(\omega t - 0.5\pi) \quad . \qquad (16)$$

VI. MODELING OF FILTER EQUIPMENT WITH AC PULSE REGULATOR

For the computer modeling software PSIMv9.0 is used. The model is presented in Fig. 4 and main parameters for it are obtained from the calculations in part IV of the current paper.

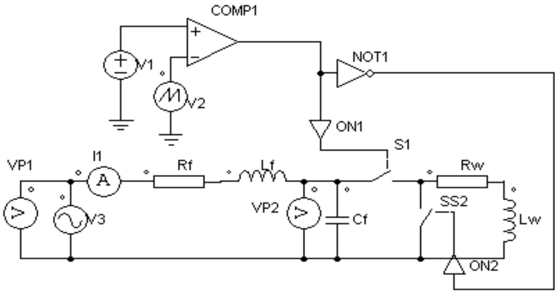

Fig. 4. System's simulation computer model.

Elements Rf-Lf-Cf operate as the 2nd order filter, chain Rw-Lw acts as a reactive inductive power consumer. The system is controlled by PWM control, realized on elements V1-V2-COMP1. Results obtained from model are shown in table 1. It can be seen from this table, that the system changes its patterns from capacitive to inductive as a function of switch S1 commutation duty ratio.

1.TABLE
REACTIVE POWER OF THE SYSTEM ON DEPENDANCE ON DUTY RATIO

Switch duty ratio; γ	**Reactive power, kvar**
0.01	-10.0
0.1	-9.81
0.2	-9.2
0.3	-8.21
0.4	-6.81
0.5	-5.01
0.6	-2.81
0.7	-0.219
0.707	0.0241
0.8	2.764
0.99	9.903

Also, we can observe, that the dependence of system reactive power is not linearly proportional to switch duty ratio. In Fig. 5 typical waveforms of grid current and capacitor voltage are shown (measured at $\gamma = 0.5$).

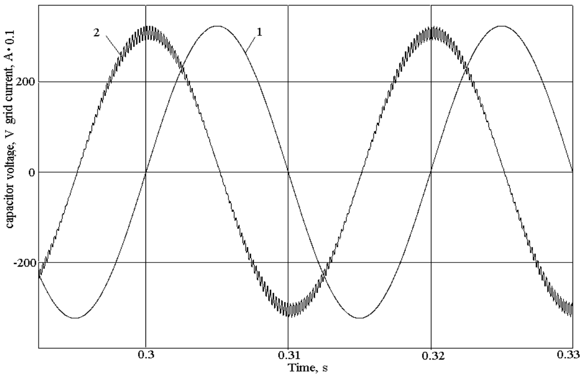

Fig.5. Waveform of network current (2) and capacitor voltage (1), obtained on computer model.

To enhance readability of waveforms, current's values are multiplied by 10. It is easy to see, that the current is distorted much more at network voltage zero values than at the network voltage maximums. Measured THD of the network current here is 0.03649.

VII. Conclusions

1. Presented network filter parameter calculations method can be applied for engineering calculations.
2. Network filter's capacitor can be used as a reactive power source for AC pulse regulator based reactive power compensation system.
3. The maximum network current distortion takes place at network voltage crossing zero line when voltage ripples also are the highest.

VII. References

[1] J.H. Kim, B.D. Min, B.H. Kwon, S.C. Won, *A PWM buck-boost AC chopper solving the commutation problem, IEEE Trans. on Ind.Electron*., vol. 45, no.5 pp.832-835

[2] J.D. Yang, L. Li, K.M. Yang, *A novel buck-boost mode single stage three level AC/AC converter, Proc. Of IEEE Industr.Electron. IECON,* 2008, pp.596-600

[3] C. Aghion, M. Lucanu, O. Ursaru, N. Luvanu, *Direct AC-AC Step-Down Single-Phase Converter with Improved Performances. Elektronuika ir elektrotehnika, vol 18, no 10,* Kaunas, 2012. pp. 33-36

[4] O. Vasilevics, I. Rankis, *Principles of Realization of Control System for a Compensator of Reactive Power on Base of Gate Commutated Thyristors. Power and El. Eng., No 30,* 2012, Riga. Pp 41-45

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Ivars Raņķis, Oļegs Vasiļevičs. Maiņstrāvas impulsregulatora tīkla filtra parametru novērtējums
Aplūkota reaktīvās jaudas kompensēšanas iekārta, kurā slodzes droseles strāvu regulē ar maiņstrāvas impulsregulatoru. Lai novērstu elektromagnētiskos traucējumus barojošajā maiņstrāvas tīklā, sistēmas pievienošana tīklam tiek veikta caur LC filtru. Tā kā sistēmā tiek ieviests kondensators, ar impulsregulatoru iespējams regulēt abu veidu reaktīvās jaudas: pie mazām impulsregulatora virknes slēdža ieslēgšanas attiecībām periodā – sistēma darbojas kā kapacitīvs mezgls, pie lielākām slēdža ieslēgšanas attiecībām – kā induktīvs mezgls. Formulēta saite starp impulsregulatora darbības parametriem, sistēmas reaktīvo elementu parametriem un sistēmas kopējo reaktīvo jaudu. Iegūtas aprēķinu izteiksmes filtra kondensatora sprieguma līknes noviržu no pamatharmoniskās aprēķinam, kā arī tīkla strāvas pulsācijas noteikšanai, kas ļauj novērtēt sistēmas ietekmi uz barojošo tīklu. Galvenais uzdevums ir atrast ieejas filtra nepieciešamos parametrus, kas noteiktu ietekmi uz kondensatora sprieguma un tīkla strāvas pulsācijām. Parādīts, ka lielākās pulsācijas veidojas brīžos, kad kondensatora spriegums maina polaritāti, t.i., pie $\omega t = \pi, 2\pi, 3\pi ...$ Pie tam kondensatora sprieguma izmaiņas izraisa filtra droseles ierobežotas tīkla strāvas izmaiņas, kas savukārt nosaka THD indikatoru. Veikta sistēmas datormodelēšana pie dažādiem parametriem un novērtēta rezultātu atbilstība aprēķinu parametriem, kas uzrāda labus rezultātus. Secināts, ka kopējās sistēmas jaudas atkarība no impulsregulatora slēdža ieslēgšanas attiecības nav lineāra.

Иварс Ранькис, Олег Василевич. Оценка параметров входного фильтра импульсного регулятора сети переменного тока
Рассмотрена система компенсации реактивной мощности, в которой нагрузкой является дроссель, ток которой регулируется импульсным регулятором переменного тока. Для устранения электромагнитных помех в питающей сети система подключена к сети переменного тока через индуктивно-емкостной фильтр. Поскольку в системе внедрен конденсатор, при помощи импульсного регулятора можно регулировать характер нагрузки: при малых относительных продолжительностях включения серийного ключа импульсного регулятора система работает как емкостной узел; при больших относительных длительностях включения – как индуктивный узел. Сформулирована связь между параметрами действия импульсного регулятора и общей реактивной мощностью системы. Получены выражения для расчета отклонения кривой напряжения конденсатора от фундаментальной, как и выражения для расчета пульсаций входного сетевого тока, что позволяет оценить электромагнитное влияние системы на питающую сеть. Главная задача состоит в оценке необходимых параметров элементов филтра, которые будут влиять на характер изменения напряжения конденсатора фильтра и тока дросселя филтра. Показано, что наибольшие отклонения тока и напряжения от синусоидального имеют место в моменты времени, когда меняется полярность напряжения конденсатора, т.е. при $\omega t = \pi, 2\pi, 3\pi ...$ При этом изменения напряжения конденсатора вызывают ограниченные дросселем изменения тока питания., что в свою очередь определяет гармонические искажения тока питания. Приведено компютерное моделирование системы при различных параметрах элементов и оценено соответствие рассчитанным теоретически и показано, что соответствие получено хорошим. Установлено, что изменения мощности узла от изменений относительной продолжительности включения ключа не являются линейными.